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jc914 U.S. PTO 60/241269

INVENTOR(S)

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☐ Additional inventors are being named on the ___ separately numbered sheets attached hereto

TITLE OF THE INVENTION (280 characters max)

Micro-Electro-Mechanical Systems for Optical Switches and Wavelength Routers

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ENCLOSED APPLICATION PARTS (check all that apply)

☑ Specification Number of Pages [ ]
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Respectfully submitted,

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Date 10/17/00

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Docket Number: [ ]

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Number 2 of 2

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STATEMENT BY A NON-INVENTOR SUPPORTING A CLAIM BY ANOTHER FOR SMALL ENTITY STATUS

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Applicant, Patentee, or Identifier: Vlad Novotny

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UNITED STATES PROVISIONAL PATENT APPLICATION

TITLE: MICRO-ELECTRO-MECHANICAL SYSTEMS FOR OPTICAL SWITCHES AND WAVELENGTH ROUTERS

APPLICANT:

VLAD NOVOTNY & PARVINDER DHILLON

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MICRO-ELECTRO-MECHANICAL SYSTEMS FOR OPTICAL SWITCHES AND WAVELENGTH ROUTERS

Field of the Invention

The present invention generally relates to designs and fabrication processes of Micro-Electro-Mechanical Systems (MEMS) devices for optical cross connect switching arrays and wavelength routers used in optical communication networks.

Background

In "all optical networks" that use only optical signals (without conversion of optical signals to electrical signals and then from electrical signals back to optical signals), the networking systems have to be able to switch digital data carried on multiple wavelengths and at multiple data rates, from any incoming fiber into any other outgoing fiber and vice versa. This is accomplished by optical cross connect switching arrays. The actual switches that form an array are either digital or analog. Digital switches have typically only two states – on and off, generally with light being reflected in the on-state and transmitted in the off-state. Analog switches, on the other hand, have an infinite number of positions that can redirect the optical beams. Analog and digital switches have a number of advantages and disadvantages that vary with the size of the cross connect switch. For the smallest arrays, digital switches are preferable. For medium and large switching arrays, digital approach is not feasible due to insertion losses, cross talk, power dissipation and additional performance detractors. A number of different technologies can be used to build switching arrays. This patent application addresses the design and fabrication of analog switches using Micro-Electro-Mechanical System (MEMS) techniques.

Another important device in "all optical networks" is a wavelength router. It permits transmission of signals at different specific wavelengths at different times into destinations from a single fiber source that contains signals carried at multiple

wavelengths. One class of wavelength routers consists of incoming fiber, wavelength division demultiplexer and optical cross connect switch.

The analog switching mirrors can be driven electrostatically, electromagnetically, piezoelectrically, or thermally. This patent application concentrates on, but is not limited to, design and fabrication of mirrors that are driven electrostatically. The desired design has to deliver the following characteristics:

1. optical performance with low insertion loss and minimum cross talk
2. low driving voltages, requiring hinges of low stiffness
3. high sensitivity, with large deflection angles per unit voltage
4. one or two axis motion of mirrors
5. maximum electrostatic stability regime for operation
6. no electrical shorting, even when physical contact occurs between movable and fixed components of mirrors
7. small footprint for the frames and hinges surrounding mirrors
8. long term mechanical reliability without fatigue or breaking of hinges
9. simple, high yield fabrication process and reliable separation technique for devices.

In order to maintain the best flatness of mirrors and achieve low hinge stiffness, the mirror thickness and thickness of hinges have to be decoupled. The additional aim of this application is to fabricate hinges with single crystal silicon that yield the best mechanical reliability compared with polycrystalline materials such as polysilicon. The preferred fabrication processes for cross connect switches and wavelength router applications are also described in this application.

Summary

Multiple designs of Micro-Electro-Mechanical System mirror arrays are disclosed with electrostatic driving, in parallel plate and rotational comb configurations. Low stiffness hinge designs allow electrical driving with relatively low voltages. Mirror thickness and hinge thickness are decoupled to preserve mechanical flatness of mirrors, and at the same time attain high deflection sensitivity. Preferred fabrication processes are

based on bulk micromachining of multilayer and single layer silicon-on-insulator wafers, and deep reactive etching of single crystal silicon. Two part system is fabricated with movable mirrors on one wafer and fixed electrodes and driving electronics on a separate wafer and then assembled, with alignment locks and keys included in the two respective wafers. These two-axis devices are used primarily in large optical cross connect switching arrays while, one axis devices are typically employed in small cross connect switching arrays and wavelength routers.

Brief description of the drawings

Figure 1: General architecture of analog optical cross connect switching array.

Figure 2: General architecture of wavelength router employing cross connect switching array.

Figure 3: Schematic diagram of parallel plate capacitor, two-axis electrostatic mirror design for optical cross connect switch.

Figure 4: Two axis, rotational comb electrostatic mirror design for optical cross connect switch.

Figure 5: Hinge design and the corresponding electrode design for parallel plate option with double, straight serpentine hinges oriented parallel to square mirror edges.

Figure 6: Hinge design and corresponding electrode design for parallel plate option with two sets of hinges for each rotational axis - serpentine and straight hinge combination.

Figure 7: Hinge design and corresponding electrode design for parallel plate option with straight, serpentine hinges oriented perpendicularly to square mirror edges.

Figure 8: Hinge design and corresponding electrode designs for parallel plate option with serpentine hinges having variable spring constant.

Figure 9: Double serpentine hinge design and corresponding electrode design for parallel plate option with circular mirror.

Figure 10: Radial serpentine hinge design and corresponding electrode design for parallel plate option with circular mirror.

Figure 11: Curved, circumferential serpentine hinge design and corresponding electrode design for parallel plate option with circular mirror.

Figure 12: Curved, circumferential, variable spring constant serpentine hinge design and corresponding electrode design for parallel plate option with circular mirror.

Detailed description of the preferred embodiments

The schematic architecture of N x M cross connect switch is shown in Figure 1 in which multiple components are represented by the single component. The cross connect switch consists of two sets of fibers and alignment structures with N and M fibers 31 and 41 respectively, two sets of microlens arrays 33 and 42, two sets of analog mirrors 34 and 44, two sets of positioning devices 32 and 43, communication optics 53 and 54 and control electronics 51, 52, and 55. For N incoming fibers and M outgoing fibers, it is necessary to have 2N (if N > M) analog mirrors in order to switch light from any incoming fiber 31 to any outgoing fiber 41 and vice versa

Another application of MEMS mirror cross connect switching arrays is shown in Figure 2 where the general architecture of wavelength router is depicted. The light with multiple wavelengths is coupled from a fiber 81 into the lens 82 and wavelength division de-multiplexer 83. The demultiplexer can be of arrayed waveguide grating type, interference filter type or fiber Bragg grating type. Considering only arrayed waveguide grating 83, light enters into the free space region 84, propagates through waveguide region 85 and then exits from another free space region 86. k signals at k wavelengths are spatially separated as they exit from the free space region 86. Light with each specific wavelength is allowed to fall onto a specific mirror of array 87. The light is redirected from each mirror in the first array 87 onto a selected mirror in the second mirror array 88 and the beam reflected from this mirror is directed onto the selected output focusing lens 89 and fiber 80. Mirror arrays 87 and 88 are usually one-dimensional arrays in order to match the spatial distribution of multiple beams exiting from arrayed waveguide 83. MEMS mirrors 87 and 88 have to be two axis mirrors despite of the fact that one dimensional arrays are used, because two dimensional positioning is needed to couple the light beams into the core of outgoing fibers 80.

A schematic diagram of the two axis MEMS mirror is included in Figure 3. The movable mirror 66 is suspended on two sets of hinges 67 that allow angular deflections in one direction. In turn, these hinges are attached to inner frame 65 that has another set of hinges 68, that provide the deflection in the second direction. Only schematic hinges are shown in this figure, the actual hinges will be presented below. The cross section of the electrostatically driven mirror is shown in Figure 3b. The top electrode 70 on the movable mirror 66 and inner frame 65 defines the common electrode of four parallel plate capacitors. There are four bottom electrodes 61-64 that constitute the opposite electrodes of the above mentioned capacitors. The driving electronics is included below these electrodes for larger mirror arrays and it is connected to electrodes with vias 78. For smaller arrays and one dimensional arrays, the driving electronics can be on separate wafers and leads can be routed on the surface that contains the bottom electrodes 61-64.

An alternate embodiment of electrostatic driving of mirrors is included in Figure 4. In this case, rotational motion is generated by attractive forces between oppositely charged combs 90 or 91 of edge capacitors. Again, two sets of hinges 92 and 93 are employed to provide rotational motion in two directions, however, in this case, with more practical hinges described below. Up to six leads (not shown in the figure) are needed to connect electrical voltage sources to combs. For large arrays, it is not possible to run leads on the same plane as that of rotating electrodes 91 or 92, and therefore leads have to be routed along the walls of the top wafer onto the lower wafer that contains driving electronics.

Hinge design is the critical component of the high performance electrostatic mirrors. The length, width, thickness and cross-sectional shape of hinges determine the stiffness, and consequently, the voltages required to achieve desired deflections. The hinge stiffness is proportional to the hinge width and the third power of hinge thickness and inversely proportional to hinge length. The hinge thickness has to be optimized so that the stiffness is minimized but ensuring that the structure is not too fragile, so that it would survive separation after fabrication, handling during assembly and shock and vibration in a typical operating environment. When the same low thickness is employed for both mirror and hinges, the lack of flatness of the mirror would lead to excessive wavefront distortions of reflected light. Consequently, in most cases, the mirror thickness

will be greater than hinge thickness and the fabrication process has to be capable of generating these two thicknesses. In addition, hinge width is limited by processing (lithography and etching), and reasonable widths do not lead to acceptably low stiffness, unless the length of hinges is much greater than that which the straight hinges can provide. The solution is to use single, double, triple or quadruple serpentine hinges, as illustrated in Figure 5 double serpentine hinges 102 and 103. Another challenge is to pack the mirror 101, two sets of hinges 102 and 103 and frame 104 into as small area as possible, so that optical components can be smaller and the overall dimensions of the cross connect switching system can be reduced. Smaller mirror arrays allow larger number of devices to be built on a given wafer, thus reducing the cost of these mirror arrays. Furthermore, smaller structures have higher resonance frequencies, which improve switching and addressing times for the mirror array. Moreover, the position sensing system can have lower resolution, when shorter optical path is used as with smaller devices. The bottom part of Figure 5 contains four electrodes 105 - 108 that are used in conjunction with the top common electrode 109 to generate positive and negative angular deflections in two directions.

As the stiffness is decreased, the actual axis of rotation is shifted from the geometric axis of rotation. This leads to reduction of deflection angles, for a given gap between capacitor plates. The improvements can be obtained when the torsional stiffness is at least partially decoupled from stiffness normal to the plane of the mirror. This can be accomplished by combinations of serpentine 111 and short straight hinges 112, illustrated in Figure 6. Another embodiment that reduces displacement in direction normal to the plane of the mirror is shown in Figure 7. In this case, combination of serpentine hinges 121 that run parallel with the axis of rotation and short straight hinges 122 leads to reduction of rotational offset.

The improvement of resonant and vibrational behavior can be achieved with variable spring constant serpentine hinges 131 displayed in Figure 8. Additional option with double serpentine hinges 132 and circular mirror 133 is included in Figure 9. Further improvement of mechanical performance can be obtained with design in Figure 10 where serpentine hinges 141 are oriented almost radially around circular mirror 142. In Figure 11, the circumferentially curved quadruple serpentine hinges 151 provide very

low stiffness around circular mirror 152. The most efficient packing of mirrors is achieved with design in Figure 12 with circumferential, variable spring constant hinges 161.

In order to prevent electrical shorting when mechanical contact occurs between movable mirror or frame and bottom electrodes, the bottom electrodes are fabricated to be slightly reduced on rotational edge compared with the dimensions of the mirror and frame. In Figure 5, the edges 109 and 110 are slightly shifted toward the center of mirror compared with edges of mirror 114 and edges of inner frame 115. Only small decrease of these critical dimensions is allowed so that torque generated by electrostatic forces is not perceivably reduced.

Mirror array can be fabricated with MEMS surface or bulk micromachining technologies. The methods selected for fabrication options in this patent application rely on bulk micromachining.

The preferred fabrication process for structures with different hinge and mirror thicknesses is based on bulk micromachining of double layer silicon-on-insulator (SOI) wafers. The double layer structure is produced by oxidation of silicon wafers, their lamination (internal silicon dioxide layer will be referred to as the first silicon dioxide layer), grinding to reduce the thickness of the silicon layer to the desired thickness of hinges, deposition of another silicon dioxide layer (the second silicon dioxide layer), lamination of another silicon wafer and then repeating the process of grinding the wafers to the desired thickness, approximately equal to the mirror thickness. Alternatively, epitaxial growth of single crystal silicon is substituted for grinding of one or both silicon layers. Epitaxial option offers a better control of thin layers, with better thickness uniformity than produced by grinding.

The fabrication steps with double layer SOI wafer are as follows:

a. oxidation of both sides of the silicon wafer
b. photolithography and etching of silicon dioxide of the bottom side of SOI wafer; separation lines and alignment keys are also etched
c. deep, wet silicon etching of the bottom side of the SOI wafer, with the first internal silicon dioxide layer acting as the etch stop

d. photolithography on the top side of the wafer to produce the open areas in final structure and etching of silicon dioxide

e. deep, dry reactive ion etching of silicon with the second internal silicon dioxide as the etch stop

f. photolithography for hinges and open areas and etching of silicon dioxide

g. deep, dry reactive ion etching of silicon hinges and open areas in the final structure with the first internal silicon dioxide layer as the etch stop

h. etching of silicon dioxide in the exposed areas to open all gaps in silicon

i. metallization of top and bottom with metal adhesion layer(s) and high reflectivity material such as gold

j. driving electronics on the bottom wafer

k. deposition of insulating layer

l. photolithography and etching of vias for electrical contacts between electronics and electrodes

m. photolithography and silicon etching of gap defining grooves and locks of alignment structures

n. deposition of metallic layer for electrode fabrication

o. photolithography and etching of conductive electrodes on the bottom wafer

The fabrication of structures with the same thickness of hinges and mirrors is performed with the single layer SOI. The fabrication process is simplified compared with the above process for double layer structures by eliminating steps f and g. Single layer SOI can also be used for fabrication of movable mirrors with different hinge and mirror thicknesses by using timed etching to define hinge thickness. Alternatively, this fabrication can be accomplished using boron doped wafers or by etching of single silicon wafers and using timed etching to define hinge and mirror thicknesses. The control of

thickness and its uniformity will be very much inferior to processing that employs the double or single layer SOI wafers.

Rotational comb designs have leads incorporated on movable electrodes and no bottom electrodes are required. The leads are brought along the walls toward the bottom wafer that contains driving electronics. The interconnections between the top and bottom wafers are fabricated with solder reflow.

Finally, optical end-point detection of etching depth can be employed to fabricate these devices without SOI and without boron doping techniques by using the point where all silicon is removed in the desired open areas. The control and uniformity of hinge and mirror thicknesses is best when double layer SOI fabrication is employed. The control is less precise with single layer SOI wafers and the worst in the above outlined processes with standard, non-SOI wafers and optical end point detection.

Separation of these mechanically delicate structures is ideally done by dry etching techniques. Diamond cutting, wet etching or cracking to separate arrays from each other is difficult due to low stiffness and fragility of these structures leading to low yields. Dry silicon etching with photoresist or contact mask, photoinitiated etching of silicon and dry removal of photoresist (if used in the last etching step) are additional processes suitable for separations of arrays from the wafer.

Claims

What is claimed is:

1. One and two axis electrostatically driven mirror structures with low stiffness hinges and driving electronics.
2. Mirror structure of Claim 1 with parallel plate capacitor geometry.
3. Mirror structure of Claim 1 with rotational comb configurations.
4. Mirrors of Claim 1 that are rectangular.
5. Mirrors of Claim 1 that are circular.
6. Serpentine hinges of Claim 1 that are of single serpentine type.
7. Serpentine hinges of Claim 1 that are of multiple serpentine type where number of turns exceeds one.

8. Hinges of Claim 1 that consists of double hinge structure with a combination of serpentine and straight hinges.
9. Serpentine hinges of claim 1 that have parallel entries into the body of mirror and frames.
10. Serpentine hinges of claim 1 that have perpendicular entries into the body of mirror and frames.
11. Hinges of claim 1 that have combination of parallel and perpendicular entries into the body of mirror and frames.
12. Hinges of Claim 1 that are oriented perpendicular to axes of rotation.
13. Hinges of Claim 1 that are oriented parallel with axes of rotation.
14. Hinges of Claim 1 that contain a serpentine and straight components.
15. Hinges of Claim 1 that are of serpentine type and are oriented radially to the circular mirrors
16. Hinges of Claim 1 that are of serpentine type and are oriented circumferentially to the circular mirrors
17. Hinges of Claim 1 that are of serpentine type and have variable spring constant.
18. Hinges of Claim 1 that are high purity single crystal silicon.
19. Locking and alignment features on wafers containing mirrors of Claim 1.
20. Trenches on bottom wafer of mirror assembly of Claim 1 permitting smaller gap spacing between top and bottom electrodes than the full thickness of top wafer.
21. Spacers placed between the top and bottom electrodes of mirrors of Claim 1 that serve to create gap spacings between electrodes that are greater than the thickness of the top wafer.
22. Driving electronics of Claim 1 that is built below the bottom electrodes for large mirror arrays.
23. Driving electronics of Claim 1 that is built on separate wafer for smaller mirror arrays.
24. Solder reflow method to interconnect the movable rotational comb mirror leads to electronics on the separate wafer.

25. Dimensional control of bottom electrodes of mirrors of Claim 1 to prevent electrical shorting when mechanical contact of movable mirror and bottom plate occurs.
26. Fabrication process for mirrors of Claim 1 based on double layer silicon-on-insulator structure, yielding different thickness of hinges and mirrors, high smoothness and reflectivity of mirror surfaces.
27. Fabrication process for mirrors of Claim 1 based on single layer silicon-on-insulator structure, yielding different thickness of hinges and mirrors, high smoothness and reflectivity of mirror surfaces.
28. Fabrication process for mirrors of Claim 1 based on single layer silicon-on-insulator structure, yielding the same thickness of hinges and mirrors and high smoothness and reflectivity of mirror surfaces.
29. Fabrication process for mirrors of Claim 1 based on two boron doping processes, yielding the different thickness of hinges and mirrors and high smoothness and reflectivity of mirror surfaces.
30. Fabrication process for mirrors of Claim 1 based on one boron doping process, yielding the same thickness of hinges and mirrors and high smoothness and reflectivity of mirror surfaces.
31. Fabrication process for mirrors of Claim 1 based on bulk micromachining process with optical end point detection, yielding mirrors of high smoothness and reflectivity.

Abstract

Designs and fabrication processes for Micro-Electro-Mechanical System optical switching arrays are described. Electrostatic driving in parallel plate and rotational comb configurations is used. Multiple low stiffness hinge designs are disclosed. Mirror thickness and hinge thickness are decoupled. Preferred fabrication processes are based on bulk micromachining of multilayer or single layer silicon-on-insulator wafers.